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14. This seedling project continues to focus on developing and demonstrating key improvements that are needed for successful application of spin-based devices in nanoscale high-frequency signal processors, on chip microwave spectroscopy, and active smart materials. The devices one which we have concentrated effort are spin-transfer nano-oscillators (STNOs) and spin torque diodes (STDs). STNOs and STDs offer advantages over existing voltage controlled oscillators/ mixers/detectors including a small form factor (100 nm for a single device, < 100 µm for a 1000 element array), wide tunability range, low power, low capacitance (1 fF), insensitivity to temperature, radiation hardness, integrability with CMOS, and integrability with a wide range of traditional and nontraditional substrates. The advances needed to bring this technology to a level of maturity for practical applications in spectroscopy and signal processing include: increasing STNO power output above 1 µW (with linewidths below 20 MHz), improving STD sensitivity to > 100 V/W, demonstration of operation at frequencies ≥ 100 GHz, demonstration of phase coherent STNO arrays, and coupling STNOs and STDs to compact, planar antennas.

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High-Frequency Spin-Based Devices for Nanoscale Signal Processing, On-Chip Microwave Spectroscopy and Active Microwave Materials

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Final Report

Contents

Overview

This seedling project continues to focus on developing and demonstrating key improvements that are needed for successful application of spin-based devices in nanoscale high-frequency signal processors, on chip microwave spectroscopy, and active smart materials. The devices one which we have concentrated effort are spin-transfer nano-oscillators (STNOs) and spin torque diodes (STDs). STNOs and STDs offer advantages over existing voltage controlled oscillators/ mixers/detectors including a small form factor (100 nm for a single device, < 100 µm for a 1000 element array), wide tunability range, low power, low capacitance (1 fF), insensitivity to temperature, radiation hardness, integrability with CMOS, and integrability with a wide range of traditional and nontraditional substrates. The advances needed to bring this technology to a level of maturity for practical applications in spectroscopy and signal processing include:

- increasing STNO power output above 1 µW (with linewidths below 20 MHz),

- improving STD sensitivity to > 100 V/W

- demonstration of operation at frequencies $\geq$ 100 GHz,

- demonstration of phase coherent STNO arrays, and

- coupling STNOs and STDs to compact, planar antennas.

In addition to demonstrating these improvements in spin-based device performance we are working to integrate spin-based devices into a prototype high-frequency systems, including a high-frequency adaptive phase shifter. Progress on this effort will lay the ground work for incorporation of spin-based technology into DoD systems. Systems that could be enabled by spin-based technology include:

- high-speed signal decoding by the massively parallel nanodevice architecture for rapid threat detection for tanks, vehicles, and military personnel;
- nanoscale on-chip microwave spectrometers for material detection and characterization;
- new types of secure ultra-broadband battlefield communications;
- nanoscale chip-to-chip communication channels; and
- novel active materials that can perform phase sensitive detection of microwave radiation and re-emission of arbitrary microwave signatures.

This report summarizes progress in these areas as well as milestones/goals for ongoing work.

Progress on Spin Torque Nano-Oscillators
NIST

Deliverable: Serial STNO arrays.

We have successfully fabricated STNO devices into serially connected arrays. In this device architecture the microwave output from each device is injected into the others in the array. For a sufficiently large microwave voltage the devices will phase lock to one another, assuming that the natural oscillation frequencies of the devices are sufficiently close to one another. The arrays consist of N devices where N=1,2,3,5 or 9. In general, this power combining scheme will yield a combined power output that scales as N. We have begun initial measurements of the phase locking and power combination in these arrays. For certain device geometries and currents, we have successfully demonstrated both phase locking and power scaling in arrays consisting of two devices (Fig. 2). At 10 mA the spectral output from the two-device arrays shows a single peak, whereas at 11 mA the output clearly shows the individual outputs from the two devices. When locked, the linewidth of the oscillation is much narrower than when unlocked, and the power is approximately the linear combination of the individual device powers. Similar locking effects have been measured in the arrays having up to five devices, and the analysis of the locking behavior is underway.
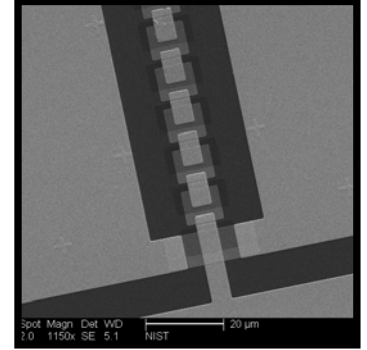

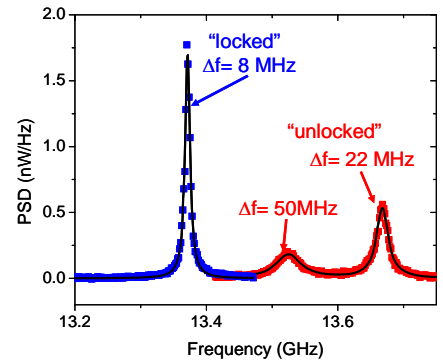Fig 1. SEM image of a segment of a nine device serial array.

Fig 2. Data showing phase-locking of two serially connected devices. Note that the amplifier gain of 30dB has not been divided out.

Deliverable: Adaptive STNO Phase Shifter.

We are in the process of completing the circuitry in order to detect and phase shift the output from an STNO device using external circuitry. We have designed and built the digital signal processor (DSP) that can detect the STNO output by digitizing and performing a Fourier transform on the signal from a device. The bandwidth of the feedback from the DSP board is roughly 3MHz. This bandwidth should be sufficient to perform active feedback on vortex mode oscillators that have free-running linewidths of approximately 300 KHz. We are on schedule to perform the adaptive phase shifter demonstration by the end of the year. The designed circuitry will also serve to control the STNO in a phase locked loop. This will additionally allow us to perform active feedback on the devices in order to improve their spectral properties.

Deliverable: Microwave signals without an Applied Field.

We have successfully demonstrated microwave emission from a STNO without an applied magnetic field. When there is no external magnetic field applied to a device, the field generated by the current flowing through the STNO becomes sufficient to seed the magnetization into a vortex pattern. Upon generation of this vortex state, the spin transfer effect induces the core of

the vortex to undergo oscillation. The power output associated with this dynamical mode is typically in the several nW to 10 nW range. The frequency of these dynamics ranges from 100MHz to 1GHz. Although this is a relatively low frequency range, the precession is very coherent having linewidths on the order of 300 KHz.

Deliverable: Output Powers >1μW.

While power outputs at the microwatt level have not yet been achieved, there has been significant progress towards this goal. We have found that single STNO devices that incorporate Co/Ni multilayers as the free layer routinely have power outputs of roughly 20 nW (Fig. 3), and additionally have the advantage of higher operating frequencies than the more conventional devices based on NiFe alloys. By combining several of the devices into a serial array, as discussed above, signals on the order of several hundred nW should be attainable. We are also in the process of investigating dynamics in MgO based tunnel junction devices. We are processing MgO based tunnel junction films that were supplied by Freescale Semiconductor into STNO devices. Seagate has also supplied MgO based hard-disk drive read heads that should act as STNO devices. We are waiting for a non-disclosure agreement to be supplied by Seagate before starting measurements.
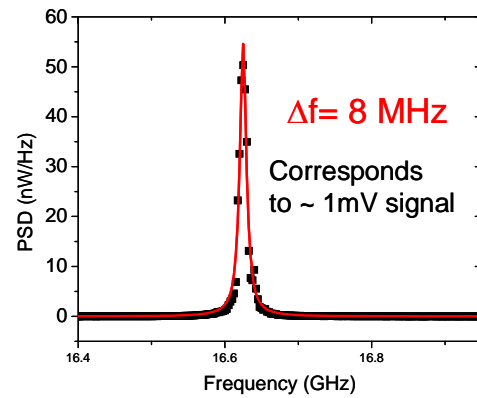

Fig 3. Output from a Co/Ni based STNO. Corresponds to approximately 20 nW, about 10 times larger than typical NiFe .device.

High-Frequency Spin-Based Devices for Nanoscale Signal Processing, On-Chip Microwave Spectroscopy and Active Microwave Materials

Cornell University

The Cornell goals within this Seedling project were:
- To develop magnetic tunnel junctions to act as spin-transfer nano-oscillators (STNOs), with the goal of achieving output powers above 1 µW with linewidths below 20 MHz in single junctions.
- To develop magnetic tunnel junctions to act as spin-torque diodes, to produce frequency-tunable microwave detectors with sensitivity greater than 100 V/W.
- To explore whether spin-torque effects acting in antiferromagnetic materials might enable the production of STNOs and spin-torque diodes with operation frequencies above 100 GHz.

1. The development of magnetic tunnel junctions to act as spin-transfer nano-oscillators (STNOs):

Spin-torque-driven magnetic oscillators made from all-metal spin valves can produce output powers on the order of 100 pW. Magnetic tunnel junctions may be capable of producing much larger signals, due to their larger magnetoresistance. However, making spin-torque oscillators using tunnel junctions requires very narrow tunnel barriers with low resistance-area products (RA ~ 1-5 Ω-μm^2) so that they can withstand the large currents necessary to sustain spin-torque-driven precession. We have performed characterization studies on optimized MgO barriers using analytic scanning transmission electron microscopy, x-ray photoemission spectroscopy, and scanning tunneling microscopy/spectroscopy, which show that optimized barriers are far from stoichiometric or single-crystalline, with significant boron incorporation that lowers the tunnel barrier and improves the transport characteristics. With such Mg(B)O barrier layers we have been able to obtain low RA tunnel junctions with tunneling magnetoresistance at the level of 150%, the point at which the spin torque efficiency effectively saturates.

We have demonstrated steady-state precession in MgO-based tunnel junctions with a resistance area product of 2 Ω–μm^2, TMR = 80%, and a circular cross section with a 60 nm diameter (fabricated by Jordan Katine at Hitachi Global Storage Technologies). Our measurements thus far indicate output powers of ~0.1 µW at I = 500 µA with linewidths of 100 MHz (Fig. 4). This represents an improvement in the output power by a factor of 1000 over previous all-metal devices, but it is not yet to our ultimate goal of 1 µW. We believe that the goal of 1 µW from a single device is achievable, and we hope in the future to explore optimization of the tunnel barrier resistance, device design, and variations in the applied current and magnetic field in order to improve the output power. We also expect to be able to obtain substantial linewidth improvements in the future with
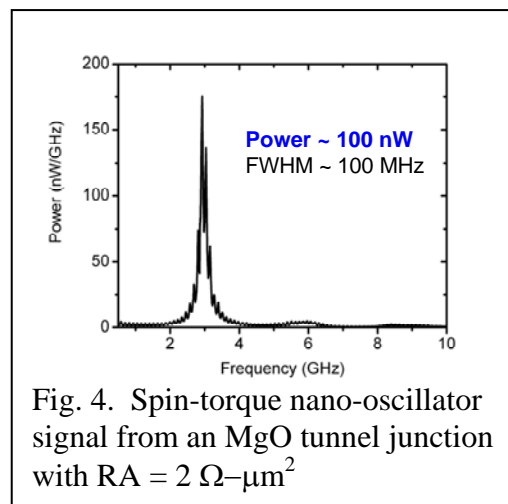

Fig. 4. Spin-torque nano-oscillator signal from an MgO tunnel junction with RA = 2 Ω–μm^2

the employment of improved micromagnetic structures in the MTJ devices, based on our all-metal spin valve studies discussed below.

Our first-generation magnetic-tunnel-junction STNOs are designed so that the magnetic free layer moves approximately as a spatially-uniform single domain. The resulting linewidths (100 MHz) are similar to those in all-metal spin-valve multilayer samples that have a similar geometry for the magnetic free layer. However, we have discovered that dramatically-narrowed oscillator linewidths can be achieved in devices designed to have spatially nonuniform magnetization distributions. Specifically, we found that metal spin valves with sidewalls that are tapered to induce an out-of-plane component of the magnetization in the magnetic fixed layer (Fig. 5) can produce large-amplitude oscillations with very narrow linewidths, ~ 2 MHz at room temperature, due to spatially nonuniform oscillations within the fixed layer (Fig. 6). We plan to use a similar tapered-sidewall design in a future generation of tunnel-junction STNOs.
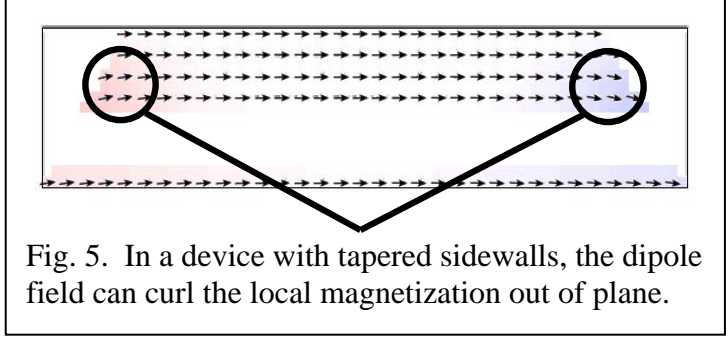

Fig. 5. In a device with tapered sidewalls, the dipole field can curl the local magnetization out of plane.
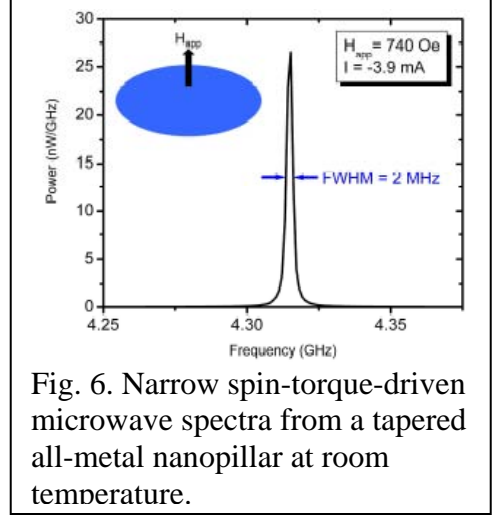

Fig. 6. Narrow spin-torque-driven microwave spectra from a tapered all-metal nanopillar at room temperature.

2. The development of magnetic tunnel junctions to act as spin-torque diodes:

From a theoretical analysis of the spin-torque diode signal, we expect that the total sensitivity should be described by the formula

$$\frac{\langle V_{mix}\rangle}{P_{inc}} = \frac{2\gamma(50\ \Omega)\dfrac{dR}{d\theta}\dfrac{d\tau}{dI}}{(M_S Vol)\sigma(R+50\ \Omega)^2},$$

where γ is the magnitude of the gyromagnetic ratio, $dR/d\theta$ is the derivative of the sample resistance with respect to the magnetization angle of the free layer, $d\tau/dI$ is the derivative of the spin torque with respect to current, $M_S Vol$ is the total magnetic moment of the free layer, and σ is the FMR linewidth. In general, $d\tau/dI$ should be weakly-dependent on the junction properties for MgO-based devices, so to maximize the diode sensitivity the most promising strategies are to ameliorate the problem of impedance mismatch by decreasing the tunnel-junction resistance R via a smaller RA product (thinner junctions) while maintaining a good magnetoresistance, and/or decreasing the total magnetic moment of the free layer $M_S Vol$ by using a lower-moment material or a thinner free layer.

We completed studies of the diode detection efficiency on two sets of MgO-based magnetic tunnel junctions: (a) a set with RA products approximately 12 Ω-μm^2, a TMR of approximately 154% with a parallel-state resistance of 3000 Ω, 2.5 nm thick CoFeB free layers, and approximately elliptical cross sections with size 50 × 100 nm^2, provided by Jonathan Sun at IBM, and (b) a set with RA products approximately 2 Ω-μm^2, a TMR of approximately 80% with a parallel-state resistance of 250 Ω, 3.9 nm thick CoFe/CoFeB free layers, and

approximately circular cross sections with a diameter of 90 nm, provided by Jordan Katine at HGST. Both sets of devices showed diode detector sensitivities in reasonable agreement with our theoretical formula. The HGST samples, by virtue of their lower resistance, exhibited the better sensitivity, with a preliminary value of approximately 50 V/W, relative to the total microwave power incident from the transmission line. The sensitivity of the IBM samples was approximately a factor of two lower, 25 V/W. We are currently checking our calibrations and preparing a paper on these results. Based on these findings, we expect that our stated sensitivity goal of 100 V/W can most easily be achieved by reducing the thickness of the magnetic free layer in the HGST devices by approximately a factor of 2.

3. Investigation into whether spin-torque effects can generate high-frequency magnetic precession in antiferromagnetic materials: The motivation of this exploratory part of the project was that the internal exchange field inside antiferromagnets can produce very high frequency oscillation modes, extending to above 100 GHz. We explored whether these modes can be driven by spin torque effects to make high-frequency STNOs. We fabricated pillar devices with a geometry similar to the ferromagnetic samples we had studied previously, containing single antiferromagnetic IrMn layers, and also IrMn layers coupled to a ferromagnetic permalloy layer. We studied the resistance of these samples as a function of current and the magnitude and angle of an applied magnetic field, looking for sudden changes in the resistance as a function of current that might indicate a transition to a current-driven precessional magnetic state. (Similar signals were the first evidence for spin-torque-driven oscillations in ferromagnetic samples.) Despite our best efforts, we did not observer any current-driven transitions, in measurements performed at both room temperature and 4.2 K.

Millimeter-Wave Operation of Spin-Torque Nano-Oscillators
University of Virginia

Summary:

The primary focus of this work is to demonstrate STNO operation at millimeter-wave frequencies, primarily at W-band (75—110 GHz) and above. To this end, we have aimed our initial work on measuring and characterizing spin-torque diodes using millimeter-wave network analyzer measurements. The goal has been to determine the RF impedance of these devices and to understand the proper embedding environment for operation at W-band and higher. Moreover, we have begun to study the behavior of STNO's under various impedance environments (using microwave tuners and load-pulling circuits) to determine the optimum embedding impedance for maximum power output.

To push the operation frequency to the 100 GHz region, we propose to use STNO/STD devices available from Cornell and NIST, integrating these devices into optimized coupling structures and placing them in a high field (3–5 Tesla) environment. The resonant emission and detection occurs at frequencies of approximately 30 GHz/Tesla and, at UVA, we have access to a number of high-field magnets capabale of producing fields in the 5—14 T range, sufficient for pushing the operating frequency well above 100 GHz. The immediate goal is to design and fabricate planar coupling structures that can accommodate single-chip STNO's, to mount these devices into the structures, and assemble the coupling probe/STNO circuit into a W-band waveguide housing. The entire assembly will be mounted to a positioner that can be placed into the core of our high-field magnet, allowing the orientation of the device and field to be varied. Millimeter-wave power generated by the device will be coupled to a broadband diode detector for measurement. As an alternative approach, we also propose to inject a millimeter-wave signal into the device and look for mixing products resulting from the STNO oscillations and input RF power.

Progress to Date:

Currently, we have STNO devices fabricated at Cornell and NIST housed in our laboratory. Figure 7(a) and (b) show the layout of these devices which are configured for measurement with a standard microwave coplanar probe.

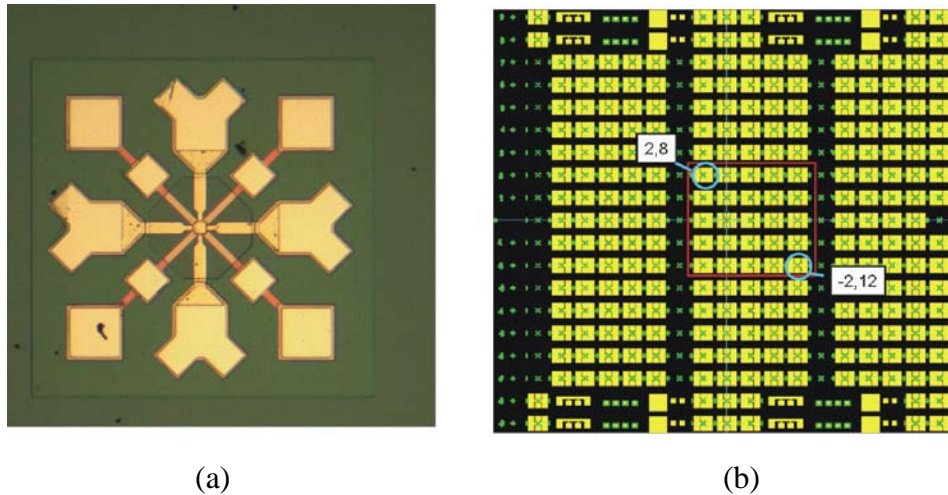(a)   (b)

Figure 7. Photograph of a single STD fabricated at Cornell. (b) Array of STNO devices from NIST. The devices are configured for planar microwave probing.

For operation in the millimeter-wave range, these devices will be separated by a dicing saw and mounted into waveguide coupling structures. To measure the device impedance at microwave/millimeter-wave frequencies, a test setup has been constructed using standard ground-signal-ground (GSG) probes, as shown in fig.8. The magnetic field is provided by two permanent magnet blocks with a magnetic induction of 0.5 T to 1.0 T. S-parameters of the device have been measured to 50 GHz with an HP8510C network analyzer and the impedances have been determined from these s-parameters (shown in figure 3). The Cornell devices consist of Py/Cu/Pt/IrMn/Co/Cu/Pt multi-layers and a SEM/layout of the device is given in figure 9(a). The measured device impedance is shown in figure 9(b). Without an externally applied magnetic field, the real part (solid line) device impedance is in the range of 25 Ω to 30 Ω over the frequencies from DC to 50 GHz. The imaginary part impedance is close to zero at low frequencies and increases with increasing of frequency (corresponding to an device inductance). Applying an external magnetic field (~ 0.5 T) along the long axis of the ellipse, the real part of the device impedance (dashed line) decreases to approximately 20 Ω, and the imaginary part increases.
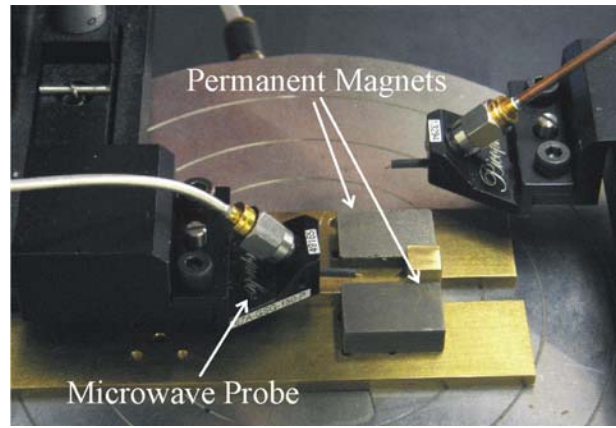

Figure 8. Photograph of Test Set-Up for measuring impedance of STNO devices.

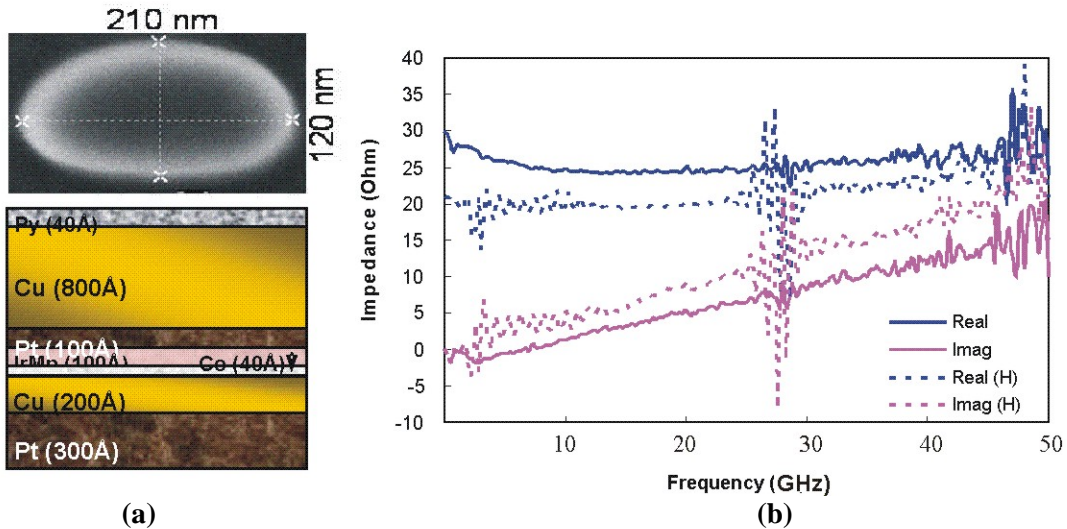(a)   (b)

Figure 9. (a) SEM/structure of a typical STD from Cornell. (b) Measured impedance (real and imaginary parts) of a Cornell STD under no applied magnetic field (solid line) and applied magnetic field of 0.5 T (dashed line).

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Microwave oscillations have been obtained from the STNO's fabricated at NIST, as shown in Fig. 10. the device consists of a multilayer of Ta/Cu/CoFe/Cu{Co/Ni)}$_{X4}$CuTa, where the CoFe and Co/Ni are the "fixed", and "active" layers, respectively. On the top surface of the multilayer, a nanoscale electrical contact (~ 40 nm) has been fabricated using e-beam lithography. The NIST nano-contact devices exhibit narrow spectrum linewidths (as seen in figure 4) which were measured with a HP8565E spectrum analyzer (0-50 GHz). The microwave emission of these devices is in X-band (8—12 GHz) when biased with a DC current of approximately 10 mA. The peak output power is measured at approximately –57 dBm with a spectrum linewidth of ~ 20 MHz. The dependence of frequency vs. DC biasing current is approximately 1.0 GHz/mA and the slope of frequency vs. magnetic filed is 28 GHz/T. In principle, an oscillation in W-band can be obtained by applying a suitably large external magnetic field (e.g. 3—4 Tesla).
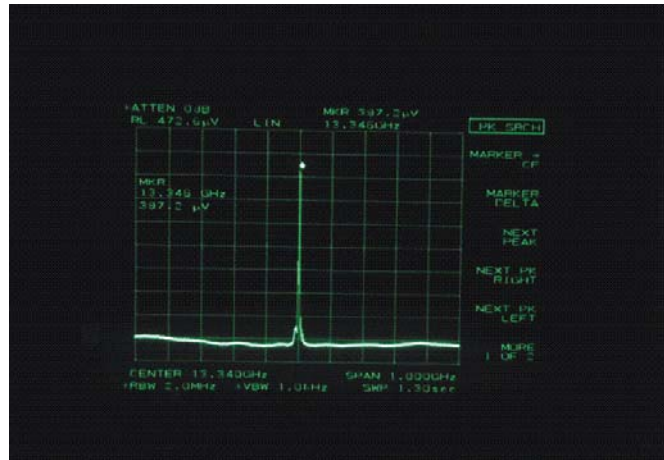

**Figure 10. Measured output from a NIST STNO device. The bias current is 10 mA and applied field is approximately 0.5 T.**

Planned Work if future funding becomes available:

W-Band Operation

The primary effort over the next few months will be focused on designing coupling structures/waveguide housings suitable for STNO operation at W-band (75—110 GHz). Information from impedance measurements up to 50 GHz and load-pulling characterization at X-band will be used to design waveguide-to-microstrip transitions and impedance transformers to optimize coupling from the STNO to a waveguide output channel. Figure 11 illustrates the basic structure. A STNO chip is mounted to a microstrip probe/matching circuit and assembled into a waveguide housing with integrated horn antenna. The entire STNO-waveguide assembly will be placed in a high-field magnet housed in The UVA physics department that is capable of producing fields as large as 4 T. The housing will be mounted on a gimble that permits that permits the relative orientation of the field and STNO to be varied.
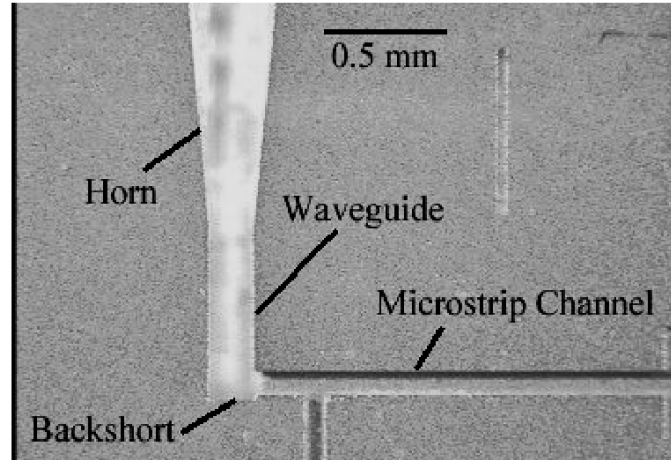
In addition to measuring output power from the SNTO's at W-band, we plan to inject an external RF signal into the waveguide to study the operation of STNO's as self-oscillating mixers.

Bias Current

STNO Chip   Probe

Output Power

(a)

Horn

0.5 mm

Waveguide

Microstrip Channel

Backshort
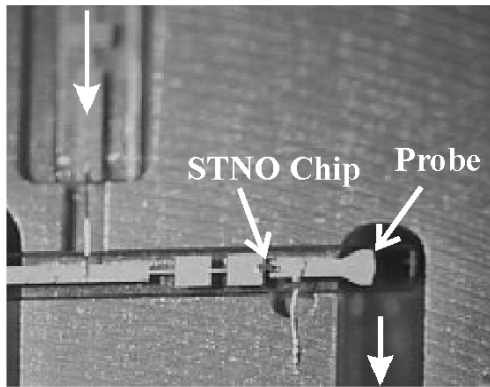
(b)

Figure 11. (a) W-band waveguide housing showing the microstrip probe ciruit, STNO chip, and output waveguide. (b) Photograph showing the output horn antenna, microstrip channel, and waveguide section.

Planned Tasks:

[1] Dicing and separation of SNTO devices from the array fabricated at NIST.
[2] Layout and fabrication of microstrip probe circuits designed for operation at W-band.
[3] Assembly of circuits into waveguide housing; assembly of gimble for orienting assembly.
[4] Measurement of STNO emission at W-band; Measurement of mixing properties of STNO using an externally-injected RF signal.

Power-Combining Arrays

To increase the power output from STNO's, we also plan to design a number of quasi-optical power-combining arrays to (1) study the mutual injection-locking properties of these devices and (2) determine the optimum conditions for efficient power-combining. Figure 12 illustrates a power-combing topology we plan to implement: individual STNO devices are mounted at the feed points of an antenna array and the array is subsequently placed into a quasi-optical resonator.

Planned Tasks:

[1] Layout and fabrication of 2 and 4-element power-combining antenna arrays for operation at 10 GHz and 100 GHz.
[2] Assembly and testing of power-combining arrays; measurement of output frequency and power; characterization of locking range and frequency-tuning
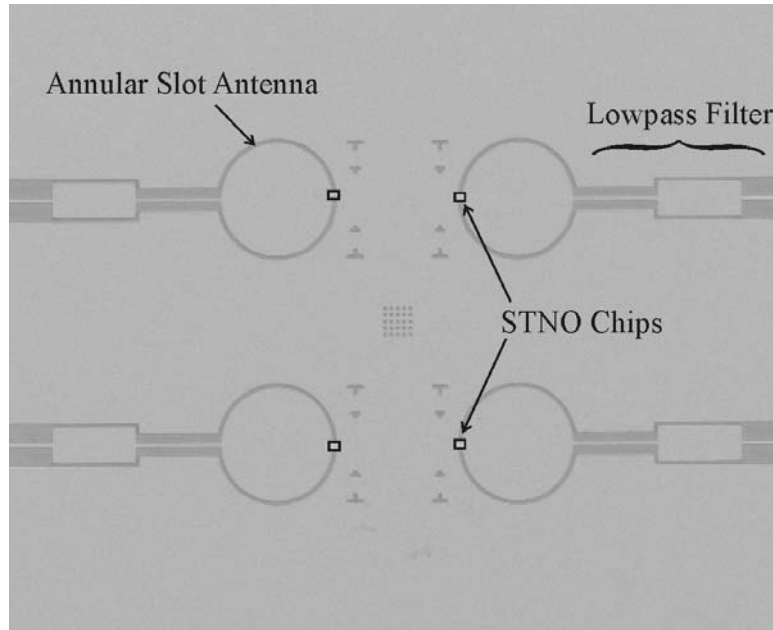
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Figure 12. Illustration of planned power-combining array for STNO's. Individual devices are mounted into an antenna array and lowpass filters permit bias current to be injected. Emissions from the individual devices are coupled to a resonator the provides the feedback needed for mutual locking of the oscillators.